Changes Occurring in Asphalts in Drum Dryer and Batch (Pug Mill) Mixing Operations

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The study was designed (a) to discover whether steam distillation of asphalt takes place in a drum dryer mixer, (b) to compare changes induced by various laboratory conditioning (aging) techniques versus those occurring in drum dryer mixers, and (c) to identify possible differences in asphalts subjected to drum dryer mixing versus batch (pug mill) mixing. Twenty-seven virgin asphalts were subjected to various laboratory conditioning experiments, including thin film oven exposure (TFO), rolling thin film oven exposure (RTFO), (small) steam distillation (SSD), forced air distillation (FAD), and rolling forced air distillation (RFAD). Various physical and chemical properties of these conditioned samples were measured. These properties were compared with those of the residues recovered from drum dryer operations for each asphalt. By comparing the laboratory conditioned residues to the recovered residues from the drum dryer operation, similarities between the variously exposed asphalts and asphalt recovered from drum dryer mixers were ascertained. This demonstrated that steam distillation does not take place in drum dryer mixers. Eight matched asphalt pairs, one used in a drum dryer mix and one in a batch (pug mill) mix, were identified among 24 virgin asphalts from Georgia by statistically comparing various physical, thermal, compositional, and molecular size properties of the virgin asphalts. Asphalts were then recovered from the mixes in which each of the eight drum dryer-batch (pug mill) asphalt pairs were used. The recovered asphalts were analyzed, and the results show the asphalt residues extracted from drum dryer operations to be slightly harder than those extracted from batch operations.

Asphalt-aggregate mixtures for pavements have been produced for many years using conventional batch (pug mill) mixing equipment. One of the most important steps in this mixing procedure is the predrying and heating of the aggregate to 250 to 350°F (122 to 177°C) before combining with asphalt to obtain the mix (*1*).

In the last 20 yr, a drum dryer mixing technology has been developed for obtaining pavement mixtures. In the drum dryer process, a drained but undried aggregate is continuously fed into the rotating drum mixer, flame heated from 250 to 300°F (122 to 149°C), and then mixed with a continuous stream of liquid asphalt to produce a mix that continuously exits at the discharge end of the mixer (*1*, pp. 47–56). The main advantage of this mixing procedure is that it is a continuous mixing process that generates asphalt-aggregate mixes much more quickly and cheaply than do conventional pug mill mixing methods. Furthermore, aggregates do not have to be predried, but only drained, before they enter the mixer.

Drum dryer mixers are now used extensively to produce mixtures for the construction of asphaltic concrete pavements.

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PROBLEM

In recent years the paving industry has produced more and more asphaltic concrete mixes using drum dryer mixing procedures. Paving personnel have reported that mixes produced by the drum dryer procedure appear to have different physical properties than those mixes produced by conventional batch mixing methods (*2,3*). Concern has been voiced in the highway community that certain asphalts can be "steam-distilled" during hot-mix production in drum mixers (*4*). Steam distillation (*5*), the distillation of an organic compound in the presence of steam, takes place when the sum of the vapor pressures of the compound and water exceeds the pressure in the distillation apparatus (in the case of a drum mixer, normally 1 atmosphere); the compound can then be distilled at a lower temperature than its normal boiling point.

Allegedly, drum dryer mixers provide an environment in which "light ends" or low boiling materials are stripped from the asphalt by a "steam distillation" process leading to an immediate problem of possible baghouse fires and a long-term problem of poor pavement performance because of unanticipated asphalt changes during the mixing process (*4*). Other asphalt researchers have hypothesized that, in the drum dryer process, fuel oil obtained from the incomplete combustion of fuel when the aggregate is being flame-heated is being mixed with aggregate and asphalt, causing these problems (*6*). A more likely occurrence would be loss of the lowest boiling point components of the asphalt. The major difference in behavior of an asphalt run through a drum mixer, in comparison with a batch (pug mill), is that little oxidation of the asphalt would be expected in the drum mixer. Asphalt is hardened mostly by oxidation in thin film oven tests (TFO) (W. Kari, private communication), tests that simulate the changes occurring to asphalts in batch (pug mill) operations (*7*).

The Florida Department of Transportation investigated the steam distillation hypothesis (*8*). They constructed pavements using one aggregate and two asphalts, either steam distilled for 36 hr or not, mixed in either a drum dryer mixer or a

batch (pug mill) mixer. After 3 yr, all pavements are performing well with no differences in pavement performance.

APPROACH

The Federal Highway Administration (FHWA), Office of Engineering and Highway Operations Research and Development, recently completed a study to identify the changes occurring in asphalt as it is being mixed with aggregate during drum dryer and batch (pug mill) mixing operations (B. Chollar et al., unpublished data). One hundred and four loose mixes were collected from drum dryer mix operations used for paving projects during the summer of 1985 in states throughout the country. With this collection of samples, at least two distinct approaches were possible:

1. A variety of laboratory conditioning (aging) procedures, including steam distillation, were run on virgin asphalts. These residues and their paired asphalts recovered from drum dryer mixes were characterized (vide infra). By comparison of the properties of each recovered asphalt with its laboratory conditioned partner, conclusions concerning the fidelity of any given laboratory procedure to the conditions occurring in drum dryer mixers could be drawn.
2. Both drum dryer and batch (pug mill) mix operations were represented in the samples of loose mixes and virgin asphalts obtained from Georgia. Here was an opportunity to use the characterization of the virgin asphalts to match mixes from the two types of mixing plants as using the same asphalt.

The State of Georgia sent 24 mixes and corresponding virgin asphalts as part of this study; 11 of these mixes were from batch (pug mill) mixing procedures, and 13 of them were from drum dryer operations. Once drum dryer-batch (pug mill) pairs involving the same asphalt were identified, the characterization of the recovered asphalts would enable any differences between the two processes to be identified.

EXPERIMENTAL

To make the study manageable, 27 mixes and their corresponding virgin asphalts (various grades) were arbitrarily selected from various states. The asphalts were extracted and recovered from their mixes using a standard Abson method (*9*), and the recovered (REC) and virgin asphalts (VIR) were characterized (vide infra). Asphalts from the 24 Georgia loose mixes were also extracted, recovered, and characterized. The corresponding virgin asphalts used to produce these mixes were also characterized.

The following laboratory conditioning techniques were conducted using each of the 27 virgin asphalts. The resulting residues from each conditioning procedure were characterized.

Conditioning Procedures

Thin Film Oven Exposure (TFO) (10)

This standard exposure test for asphalts involves a thin film of asphalt being exposed to air at 325°F (163°C) for 5 hr. The film of asphalt is then collected and characterized. No evaporated materials are collected. This test simulates the effects of conventional batch mix procedures on asphalts as shown by the changes in asphalt characteristics (*7*).

Rolling Thin Film Oven (RTFO) Exposure (11)

In this form of the standard thin film oven exposure, the asphalts are exposed at 325°F (163°C) to air streams in rolling bottles, coating the bottles on all inner sides with films of asphalt. It differs from the TFO exposure in its use of a smaller sample size spread over a larger area in a continuous rolling manner, allowing for a more efficient oxidation of the test asphalt in less time.

The residue asphalt is then collected and characterized. No evaporated material is collected.

Small Steam Distillation (SSD) (12)

This modified American Society for Testing and Materials (ASTM) procedure using 75 g of asphalt, not 500 g, is simulating what many researchers think is the process actually occurring in the drum dryer operation (*4*). Steam is bubbled through hot asphalt and removes volatile asphalt components (water-distillable light ends) from the resulting residue. The residue asphalt is then characterized. This procedure was conducted with duplicate samples.

Forced Air Distillation (FAD)

A laboratory distillation was developed whereby an air stream is forced over an asphalt film heated to 662°F (350°C) in a closed system and any evaporated asphaltic materials are trapped and collected. The asphalt residue is then characterized. Details of this procedure are found in an FHWA report (B. Chollar et al., unpublished data). This procedure is designed to simulate the TFO procedure (*10*) with the added provision of catching any generated volatile materials. (Discussion of the trapped effluent is not reported in this paper.) The FAD was conducted on duplicate samples.

Revolving Forced Air Distillation (RFAD)

A laboratory distillation of asphalt is set up much like the FAD procedure with an air stream, but using asphalt films in a revolving container in a closed system at 325°F (163°C). Evaporated components are also collected. The asphalt residue is characterized. Details of this procedure are found in an FHWA report (B. Chollar et al., unpublished data). This procedure was designed to simulate RTFO procedures with trapping effluent and was conducted on duplicate samples (*11*).

Analytical Procedures

Various analytical laboratory test procedures were used to ascertain any like attributes or departures from such in the laboratory comparisons of asphalts and asphaltic residues.

These consisted of physical properties (penetration and viscosity), thermal properties (differential thermal analysis), functional group composition (infrared analysis), and molecular size distribution (gel permeation chromatography). The resulting data permitted a differentiation among the residues from various exposures and a characterization of the changes occurring both physically and chemically in the asphalts during conditioning. The data were also used to identify the identical Georgia virgin asphalts and the differences between recovered asphalts from batch and drum dryer mixes of like virgin asphalts.

Penetrations (Pen)

Penetrations of virgin asphalts, asphalts recovered from mixes, and residues from various laboratory conditioning experiments were obtained at 85, 77, 60, and 50°F (29, 25, 16, and 10°C) following the procedures described in American Association of State Highway and Transportation Officials (AASHTO) T49 (*13*). All penetrations at various temperatures used the time and weight specified for the penetration at 77°F (25°C).

Viscosities (Vis)

The procedures in AASHTO T201 and T202 (*13*) were used to conduct the kinematic viscosities at 275°F (135°C) and the absolute viscosities at 140°F (60°C) of virgin asphalts, asphalts recovered from mixes, and residues from various laboratory conditioning experiments.

Differential Thermal Analysis (DTA)

Differential thermal analyses were conducted using a Perkin-Elmer System 4 Controller and DTA 1700 Differential Thermal Analyzer. In this procedure asphalts were heated in air, and the energy of reaction or structure change was measured. Approximately 3 mg of sample were used, and the samples were prepared and run according to manufacturer's recommended procedures. Scans were made ranging from 212 to 1,112°F (100 to 600°C) at a heating rate of 9°F/min (5°C/min). Typical thermograms as illustrated in Figure 1 were obtained. The data consisted of determining a ratio of two areas of the thermogram produced by dropping a perpendicular from the point of lowest exothermic energy between 572 to 752°F (300 to 400°C), calculating the areas of the resulting Peaks 1 and 2, and taking the ratio of these areas ($P1/P2$). The temperature of the maximum of Peak 2 ($Tpk2$) was read directly from each thermogram. $Tpk2$ was used because only $Tpk2$, not $Tpk1$, showed appreciable variation from asphalt to asphalt.

Infrared (IR) Spectroscopy

Sample Preparation and Spectra Scan (IR) All organic materials absorb infrared (heat) radiation at various energies (e.g., in units of cm^{-1}), according to their molecular structure and, in particular, their functional group composition. In this procedure, infrared radiation was directed through asphaltic films. Absorbed radiation was measured by a detector and the infrared spectra (plot of infrared radiation absorbed versus

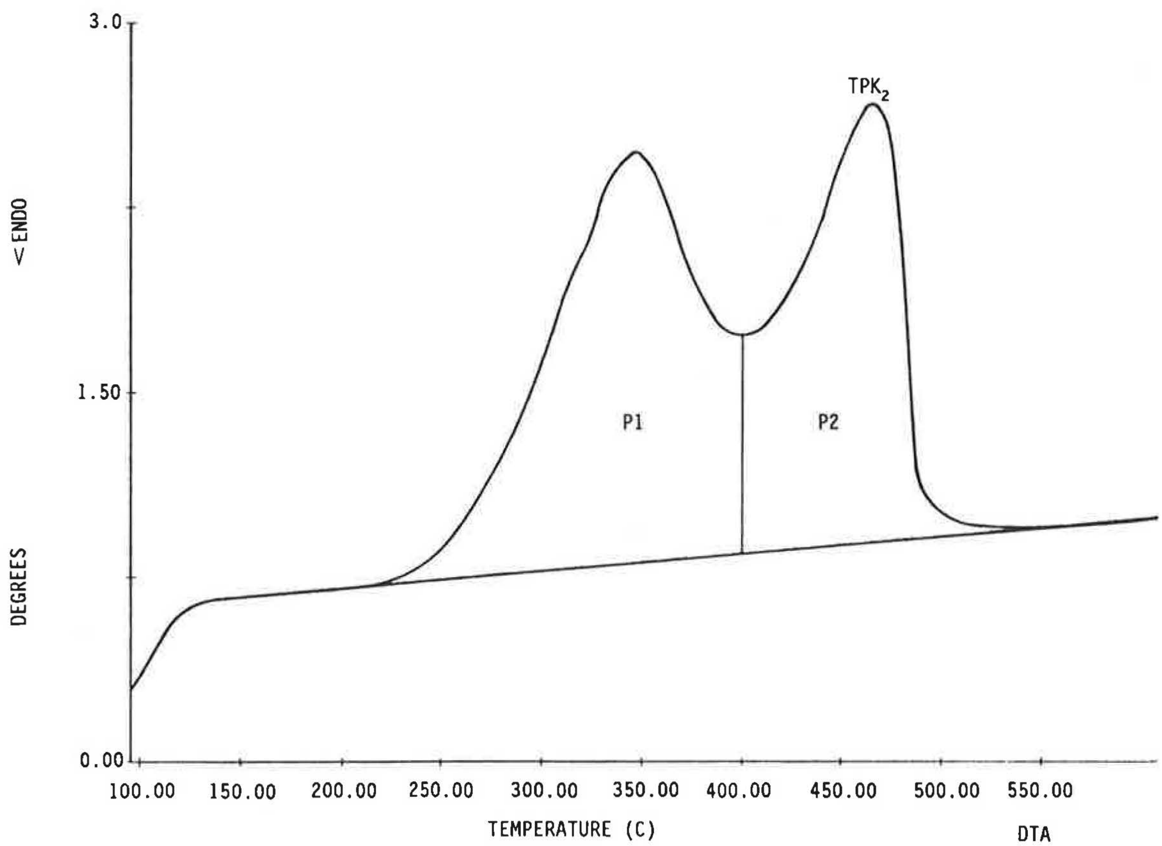

FIGURE 1 Differential thermogram of an asphalt.

energy) were produced (Figure 2). The infrared spectra were obtained using a Nicolet 390 FTIR Spectrometer. Asphalt was applied as a film to a KBr plate with a spatula containing the hot asphaltic material. Sample scans were then obtained, and the asphalt film thickness adjusted so the peak at 2,926.6 cm^{-1} fell between 10 and 20 percent transmittance (80–90 percent absorbance). Ten scans of the same sample were then taken and averaged.

Interpretation of Infrared Spectra The infrared spectra were analyzed in terms of the relative areas under peaks in different energy regions of the spectrum. Peak areas are roughly proportional to concentration for a given chemical molarity. Most differences in peak area values of radiation absorption between the virgin and recovered or laboratory conditioned asphalts were found in the following eight spectral regions:

Area	Region, cm^{-1}	Assignments (*14,15*)
1	1775 to 1670	C=O (Carbonyl Stretch)
2	1670 to 1532	Unsaturated C=O, C=C (Olefinic Stretch)
3	1180 to 1113	Secondary & Tertiary C—O, S=O
4	1113 to 983	Primary C—O, S=O
5	917 to 843	Polysubstituted Aromatic
6	843 to 785	Aromatic
7	785 to 687	Monosubstituted Aromatic C—H
8	1325 to 1281	Aromatic amine C—N or oxidized Nitrogen N—O

A computer program was prepared using procedures developed (D. Stokes, private communication) to integrate peaks in each of the preceding regions and to obtain a ratio of areas of each of the regions over the total area of those eight regions for each spectrum.

High Pressure Gel Permeation Chromatography (HP-GPC)

A high performance gel permeation chromatograph (Waters Associates) with three Ultrastyragel columns (Waters 1000°A, 500°A, and 100°A) connected in series and a UV absorption detector (Schoeffel 700) were used in this study. The data were calculated according to published procedures by P. W. Jennings and J. Pribanic (*16*) and reported as percent large molecular size (LMS), medium molecular size (MMS), and small molecular size (SMS) particles in each asphalt.

RESULTS

Comparisons of Laboratory Exposure Residues with Extracted Drum Dryer Mix Residues

For valid comparisons of the effects of laboratory aging versus those of drum dryer mixing on asphalt, the analytical data were manipulated to put the comparisons on a common basis. Table 1 shows the results of these manipulations. For exam-

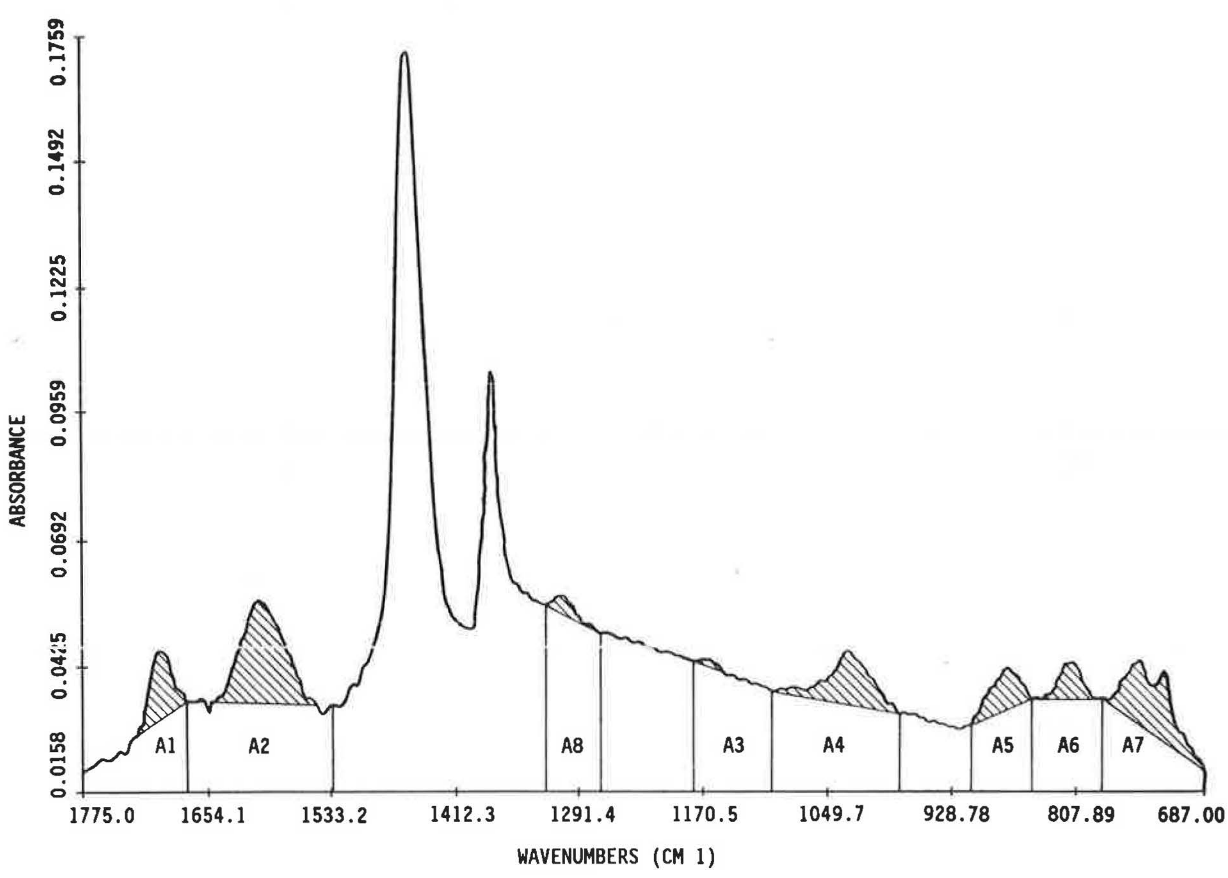

FIGURE 2 Infrared spectrum of an asphalt.

TABLE 1 PHYSICAL, THERMAL, AND MOLECULAR SIZE PARAMETER RATIOS. AVERAGES AND STANDARD DEVIATIONS OF ASPHALTS FROM DRUM DRYER MIXES AND LABORATORY CONDITIONED ASPHALTS WERE COMPARED WITH VIRGIN ASPHALTS

		REC/VIR	TFO/VIR	RTFO/VIR	FAD/VIR	RFAD/VIR	SSD/VIR
Pen 77°F	Avg	0.51	0.60	0.48	0.81	0.52	0.85
	SD	0.12	0.05	0.06	0.41	0.06	0.09
Vis 140°F	Avg	4.64	2.61	3.45	4.10	3.24	1.41
	SD	2.49	0.57	0.98	6.26	1.60	0.24
Vis 275°F	Avg	1.84	1.51	1.57	1.66	1.55	1.11
	SD	0.28	0.13	0.13	1.32	0.19	0.08
VTS	Avg	1.02	1.01	1.03	1.02	1.02	1.01
	SD	0.04	0.03	0.03	0.08	0.04	0.01
PVN_{140}	Avg	0.12	0.61	0.79	0.46	0.83	0.85
	SD	1.09	0.54	0.62	1.55	0.87	0.41
P1/P2	Avg	1.00	1.12	1.03	1.06	1.04	1.10
	SD	0.23	0.17	0.24	0.13	0.17	0.14
Tpk2	Avg	1.00	1.00	0.96	1.00	0.99	1.00
	SD	0.02	0.01	0.19	0.01	0.01	0.01
LMS	Avg	1.37	1.23	1.25	0.95	1.23	1.02
	SD	0.21	0.17	0.15	0.14	0.17	0.11
SMS	Avg	0.86	0.92	0.93	1.02	0.92	0.99
	SD	0.05	0.05	0.09	0.08	0.05	0.06

ple, different asphalts have different initial (virgin) penetrations and viscosities. To compare changes in penetration or viscosity that different asphalts undergo upon exposure to a given conditioning or mixing procedure, the penetration (or viscosity) of the recovered asphalt (REC) is divided by the penetration (or viscosity) of the virgin asphalt (VIR). If there is no change in an asphalt upon conditioning, REC/VIR = 1. If the asphalt hardens upon conditioning, as is typical, the penetration comparison is REC/VIR$<$1 and the viscosity comparison, REC/VIR$>$1. This ratio treatment was used for all analytical and derived parameters and for all types of conditioning used. Table 1 reports the average value of these ratios (with outliers omitted) and their standard deviations (SD).

From an examination of Table 1, it may be seen that both of the DTA parameters, *P1/P2* and *Tpk2*, show negligible change in the asphalts regardless of whether they are recovered from a drum dryer mix or have undergone any of the five laboratory aging procedures. Both the ratio of the two DTA peak areas (*P1/P2*) and the maximum temperature of the second peak (*Tpk2*) have values quite close to 1. Similarly, the viscosity temperature susceptibility (VTS) (*17*) shows virtually no change from unity.

To decide whether steam distillation is occurring in drum dryer mixing, the ratios for the five laboratory aging procedures are compared with the ratio for the asphalt recovered from drum dryer mix (REC/VIR). For penetration at 77°F, viscosities at 140°F and 275°F, and penetration viscosity number (PVN_{140}) (*18*), the ratio for the (small-scale) steam distillation (SSD/VIR) deviates more from the ratio REC/VIR than do the ratios for any of the other four laboratory aging procedures (TFO, RTFO, FAD, and RFAD). The HP-GPC data are not quite so clear cut. The large molecular size (LMS) parameter for SSD/VIR is unlike that for the drum dryer mix (REC/VIR) and three of the four other laboratory aging techniques. Only FAD/VIR has a value near that of SSD/VIR. The small molecular size (SMS) parameter gives similar ratios for all laboratory aging procedures, which are slightly higher than that of REC/VIR.

Laboratory treatment SSD (small-scale distillation) is a steam distillation of the virgin asphalts according to "Steam Distillation of Bituminous Protective Coatings" (ASTM D255) (*12*). Its residues appear to be more unlike the asphalts recovered from drum dryer mixtures than any of the other four laboratory treatments. This comparison negates claims of a steam distillation of light ends affecting adversely the quality of drum dryer mixtures (*4*).

In Table 2 the infrared (IR) spectroscopy parameters are handled by ratioing the infrared area ratios for the drum dryer mix recovered asphalt or laboratory aged asphalt to that for

TABLE 2 INFRARED AREA RATIOS FOR EIGHT AREAS. AVERAGES AND STANDARD DEVIATIONS FOR ASPHALTS FROM DRUM DRYER MIXES AND LABORATORY CONDITIONED ASPHALTS WERE COMPARED WITH VIRGIN ASPHALTS

		REC/VIR	TFO/VIR	RTFO/VIR	FAD/VIR	RFAD/VIR	SSD/VIR
IR Area No.							
1 (C=O)	Avg	-1.06	0.68	0.56	-0.27	0.42	1.35
	SD	5.78	2.68	0.94	3.38	2.72	3.31
2 (Unsat C=O)	Avg	0.89	1.00	1.10	1.08	1.06	1.06
	SD	0.07	0.09	0.17	0.09	0.13	0.15
3 (Tert. C-O)	Avg	-0.19	0.87	1.16	1.33	0.19	0.80
	SD	2.20	2.72	1.98	2.54	2.12	2.34
4 (Prim. C-O)	Avg	2.24	1.64	1.48	0.91	1.47	0.80
	SD	1.37	1.27	0.87	0.66	1.38	0.54
5 (Polysub Ar)	Avg	0.81	0.97	1.01	1.02	1.03	1.05
	SD	0.10	0.11	0.16	0.11	0.13	0.13
6 (Aromatic)	Avg	0.76	0.95	1.08	1.03	0.98	0.97
	SD	0.07	0.11	0.21	0.14	0.12	0.09
7 (Monosub Ar)	Avg	0.81	0.96	0.76	0.93	0.94	1.02
	SD	0.12	0.16	0.36	0.11	0.17	0.15
8 (Ar Nitrog,	Avg	0.81	1.04	1.05	1.00	1.07	1.17
C-N or N-O)	SD	0.16	0.17	0.17	0.22	0.20	0.14

the virgin asphalt. Thus the IR data are handled just like the data recorded in Table 1. Steam distillation, SSD/VIR, is different from the asphalt recovered from the mix (REC/VIR) and all the other laboratory aging procedures for four of the IR peaks: Peaks 1, 4, 7, and 8. For the other peaks, SSD/VIR is different from REC/VIR, but not different from the ratios of at least some of the other laboratory aging procedures.

The foregoing procedures, although generally convincing that the effects of drum dryer mixing on asphalt are less like steam distillation than any of the other laboratory aging techniques considered, are not statistically based. Table 3 shows the results of the Student's paired *t*-test (*19*) comparing the ratios listed in Tables 1 and 2 of asphalts extracted from drum dryer mixes to residues of like virgin asphalts aged according to the various laboratory procedures. For any given parameter (e.g., penetration), the null hypothesis is that the mean of that parameter for an asphalt recovered from a mix is the same as the mean of that parameter for an asphalt subjected to each of the laboratory conditioning (aging) procedures. If the value of *t* exceeds the critical value that is determined by the number of degrees of freedom (essentially the amount of data) and by the confidence level sought, then the asphalt recovered from the mix is different from an identical asphalt subject to the particular laboratory conditioning procedure.

The *t* statistic shows that 14 out of the 17 parameters are statistically different for the steam distillation (SSD/VIR) as compared with the drum dryer mixer recovered asphalt (REC/VIR). This is a greater number of points of difference than for any of the other four laboratory aging procedures. The next most different procedure is the TFO with 13 points of difference, followed by RTFO with 12 points of difference, followed by a tie between the FAD and the RFAD with only 9 points of difference.

Comparisons of Georgia Asphalts Processed in Drum Dryer Mixers Versus in Batch (Pug Mill) Plants

Because Georgia sent 11 mixes and corresponding virgin asphalts from batch (pug mill) plants in addition to the 13 from drum dryer mixers, the opportunity existed possibly to compare the two mixing processes. It was possible, or even likely, that between the two Georgia asphalts, there were instances where the same asphalt was used in both a drum dryer mixer and a batch plant. One could look for this by characterizing the accompanying virgin asphalts and looking for drum dryer mixer–batch plant pairs. Upon identifying such pairs, if indeed any existed, the asphalt binders recovered from their associated mixes could be characterized and any differences between asphalt processed in a drum dryer mixer and in a batch plant could be determined.

It was assumed that asphalt pairs, if they existed, would be produced by the same manufacturer. Of the 24 Georgia asphalts, the manufacturers of 18 were known. Six were from Amoco

TABLE 3 STUDENT'S *t*-TEST *(19)* OF VARIOUS PARAMETERS FOR RECOVERED ASPHALTS VERSUS LABORATORY RESIDUES

	TFO/VIR	RTFO/VIR	FAD/VIR	RFAD/VIR	SSD/VIR
Pen 77	-3.600**	1.161 NS	-3.355**	-0.557 NS	-10.026***
Vis 140	4.539***	2.331*	0.425 NS	2.046 NS	6.267***
Vis 275	5.588***	4.288***	0.723 NS	3.148**	10.569***
VTS	1.651 NS	-2.318**	-0.031 NS	0.258 NS	3.557**
PVN	-3.375**	-4.835***	-0.933 NS	-1.845 NS	3.356**
P1/P2	-2.763**	-0.570 NS	-1.472 NS	0.149 NS	-2.863**
Tpk2	-1.129 NS	1.068 NS	-1.986 NS	0.054 NS	-1.269 NS
LMS	4.758***	4.047***	9.193***	2.633*	9.478***
SMS	-5.640***	-5.554***	-9.160***	-3.317**	-9.297***
A1	-0.914 NS	-1.458 NS	-1.326 NS	-1.128 NS	-1.313 NS
A2	-5.909***	-5.890***	-10.242***	-5.942***	-5.367***
A3	-1.327 NS	-2.509*	-1.818 NS	-0.467 NS	-1.580 NS
A4	4.027***	5.548***	5.446***	4.287***	5.465***
A5	-6.340***	-4.805***	-8.961***	-6.944***	-9.631***
A6	-7.890***	-7.767***	-11.414***	-7.607***	-11.055***
A7	-4.071***	0.235 NS	-4.935***	-3.795**	-8.800***
A8	-5.633***	-7.930***	-4.076***	-5.085***	-12.172***

NS = Not Significant.

* = Significant at 95% probability level.

** = Significant at 99% probability level.

*** = Significant at 99.9% probability level.

++ = The number of samples used to calculate t for the various ratio comparisons varied from 13 to 27. The degrees of freedom used for judging the significance of t was selected based on the appropriate sample number for each ratio comparison.

Oil, Savannah, Ga.; 6 were from Shell Oil, Wood River, Ill.; 5 were from Chevron, Pascagoula, Miss.; and one was from Hunt Oil, Tuscaloosa, Ala. The procedure used was to compare statistically the various characterization parameters, which were discussed in the experimental section, for all possible pairs of asphalts within any one manufacturer category and for each asphalt of an unknown manufacturer with each asphalt of a known manufacturer. Tables 4 and 5 list the acceptable ranges for the various characterization parameters. Test virgin asphalt pairs were considered to be the same asphalt if 8 of 10 parameters for the pair in Table 4 lay within the acceptable range. There is a certain amount of arbitrariness in categorizing pairs, as each member of a pair was probably processed on a different day using slightly different processing conditions with slight variations within the crude slate. Furthermore, storage, handling, and transportation for each member of a pair would probably be different.

Using the foregoing procedure 22 asphalt pairs were identified. In 5 pairs both asphalts had been processed in a drum dryer mixer. In 9 pairs both members had been processed in a batch (pug mill) mixer. Most important, 8 pairs had one member processed in a batch mixer and the other member processed in a drum dryer. As further confirmation of the validity of these latter pairs, comparisons of the IR data showed that all drum-batch pairs had all eight infrared areas lying within the acceptable range. It should be noted in assigning these pairs that no asphalts of an unknown manufacturer matched against asphalts from more than one manufacturer. Also, in several cases one batch processed asphalt is matched against more than one drum dryer processed asphalt, and vice versa.

Having assigned the identical asphalt pairs by characterizing the virgin asphalts, recovered asphalt residues from each drum-batch pair were then characterized and compared. The results

TABLE 4 ASPHALT STANDARD DEVIATION AND ACCEPTABLE RANGES OF ASPHALT PROPERTY DIFFERENCES FOR PHYSICAL, THERMAL, AND MOLECULAR SIZE ANALYTICAL METHODS

	SD	Acceptable Range
Pen 60	0.35 dmm[a]	1 dmm[a]
Pen 77	2.0 dmm[a]	3 dmm[a]
Vis 140		100 poise[b]
Vis 275		6 cst[c]
VTS		0.033[d]
PVN_{140}		0.11[d]
P1/P2	0.05[e]	0.2[f]
Tpk2	1.19°C[e]	4.0°C[f]
LMS	0.714%[e]	2.5%[f]
SMS	0.740%[e]	2.6%[f]

[a] Standard deviations (SD) and ranges obtained from ASTM(22).

[b] This repeatability figure, based on 7 percent of the mean of the virgin asphalts, was used directly as the acceptable range(23).

[c] This repeatability figure, based on 1.8 percent of the mean of the virgin asphalts, was used directly as the acceptable range.(27)

[d] Value obtained from (Anderson, D., *unpublished data)*.

[e] Standard deviations (SD) are from previous calculations in which 24 virgin asphalts were used *(Chollar, B., et al., unpublished data)*.

[f] The ranges were calculated using the measured SD's above and multipliers given in ASTM proceedings.(25)

of Student's paired *t*-tests (*19*) are given in Table 6. It can be seen that only 5 out of 17 parameters, the penetration, the viscosity at 140°F (60°C), the HP-GPC large molecular size (LMS), and two infrared areas, are statistically different.

From the means of these five parameters (Table 6), a consistent view of the statistically significant changes is that the asphalts extracted from drum dryer mixes are harder with a lower penetration and greater viscosity at 140°F (60°C), more "polymeric" with a larger LMS content, and possibly more oxidized with a higher carbonyl and oxidized nitrogen content than asphalts extracted from batch (pug mill) mixes.

Penetration Comparisons of TFO Residues with Drum Dryer Residues

Penetrations of 56 virgin asphalts, recovered asphalts from drum dryer mixes using these virgin asphalts, and asphalt residues from TFO conditioning of these virgin asphalts are given in Table 7. This table shows that the average penetration of the recovered asphalts is lower than that of the TFO residues, or that drum dryer operations harden asphalts more than TFO conditioning does.

A paper by Granley and Olsen (*20*) discusses test results of penetrations of asphalt residues from drum dryer operations. These tests were conducted in 1972 when drum dryers were first introduced as a means of producing asphaltic concrete for paving purposes. The authors compared penetrations of virgin asphalts, asphalts submitted to TFO conditioning, and recovered asphalts from laboratory-simulated batch (pug mill) asphalt-aggregate mixing procedures with those of recovered asphalts from drum dryer operations. They found that the penetrations of 45 asphalts recovered from drum dryer operations were much higher than those of the corresponding virgin asphalts submitted to TFO conditioning tests. From this study by Granley and Olsen: "All penetration tests on recovered asphalt were well above the counterpart thin film oven test value(s) and also above those for simulated batch (pug mill) mixing tests on the original asphalt." Thus, the drum dryer operation was not hardening asphalts as much as the TFO conditioning or simulated batch mixing procedures were. FHWA endorsement of drum dryer mixing procedures for producing asphaltic concretes was greatly influenced by these results.

The 1972 penetration results directly contradict the authors' present penetration results of recovered asphalts from drum

TABLE 7 PENETRATION AT 77°F (25°C)* OF THE 56 VIRGIN ASPHALTS, RECOVERED ASPHALTS, AND THIN FILM OVEN RESIDUES

FHWA #	VIR	REC	TFO	FHWA #	VIR	REC	TFO
8509		38	135	8640	79	38	48
8517	93	38	56	8642	63	31	38
8519	142	70	86	8644	72	28	44
8521	96	34	53	8650	88	57	51
8523	73	24	44	8652	86	22	50
8525	67	38	41	8656	81	21	43
8527	108	38	64	8664	74	30	46
8533	73	32	45	8674	67	25	39
8535	73	45	45	8676	74	31	45
8537	109	53	65	8678	73	29	43
8543	104	41	63	8682	70	29	41
8561	175	28	99	8686	71	32	43
8570	98	51	66	8690	67	24	38
8572	97	61	55	8692	75	32	43
8576	102	32	56	8700	69	21	40
8588	114	52	61	8726	75	25	42
8590	66	58	43	8732	69	25	42
8592	72	26	48	8734	80	22	49
8596	145	44	77	8736	241	33	119
8600	90	35	56	8742	122	45	71
8612	134	45	75	8744	117	36	69
8615	117	53	64	8746	95	50	64
8619	116	40	65	8748	90	41	64
8621	128	55	71	8816	51	24	34
8626	125	66	67	8820	42	13	31
8628	90	35	55	8839	100	32	61
8633	87	39	60	8843	153	51	107
8637	91	43	59	8845	136	49	82

VIR	REC	TFO	
Average	95.7	37.7	58.2
Std. Dev	33.3	12.4	20.3

* All penetration values in Dmm.

TABLE 5 ASPHALT STANDARD DEVIATION AND ACCEPTABLE RANGES OF ASPHALT PROPERTY DIFFERENCES FOR INFRARED ANALYSIS

	SD[a]	Acceptable Range[b]
Infrared Area		
1	0.0072	0.0222
2	0.0167	0.0513
3	0.0129	0.0397
4	0.0439	0.1353
5	0.0153	0.0470
6	0.0060	0.0185
7	0.0347	0.1069
8	0.0058	0.0180

[a] Standard deviations (SD) are from previous calculations in which 27 virgin asphalts were used *(Chollar, B., et al., unpublished data)*.

[b] The ranges were calculated using the measured SD's above and multipliers given in ASTM proceedings.[25]

TABLE 6 STUDENT'S *t*-TEST (*22*) AND SELECTED MEANS FOR VARIOUS PARAMETERS FOR GEORGIA ASPHALT RESIDUES RECOVERED FROM DRUM DRYER VERSUS CORRESPONDING PARAMETER FOR BATCH (PUG MILL) RESIDUES

Parameter	Student's t	Mean	
		Drum	Batch
Pen 77	-3.379*	26.62 dmm	31.00 dmm
Vis 140	2.832*	19556 poise	11900 poise
Vis 275	0.989 NS		
VTS	-1.388 NS		
PVN_{140}	2.213 NS		
P1/P2	-0.424 NS		
Tpk2	-0.685 NS		
LMS	2.844*	27.46%	24.25%
SMS	-1.701 NS		
A1	-1.165 NS		
A2	4.981**	0.410	0.358
A3	1.188 NS		
A4	-1.900 NS		
A5	1.116 NS		
A6	1.593 NS		
A7	-2.230 NS		
A8	4.498**	0.024	0.021

NS = Not Significant.

* = Significant at 95% probability level.

** = Significant at 99% probability level.

dryer operations versus TFO conditioned asphalts. When drum dryer mixers were introduced, the mix temperatures were very low [250°F (122°C)] and moisture contents in the finished mix were usually very high (above 1 percent in many cases). Apparently water aided the compaction process so that the compaction could be achieved below 250°F (122°C). These lower mix temperatures and higher moisture contents resulted in less premature hardening in drum mixes (*20*).

However, stripping problems occurred with these mixes. As a result, states started to increase the mix temperatures and reduce the moisture contents in the finished mix. Thus, increased aging of asphalts has occurred.

CONCLUSIONS

1. Steam distillation of asphalts is not occurring in drum dryer operations.
2. The RFAD, TFO, and RTFO conditioned asphalts appear to have most properties closer to those of the recovered asphalt than those of the asphalts from steam distillation.
3. The recovered asphalts from drum dryer mixes, only subtly different from those from batch (pug mill) mixes, were harder [lower penetration at 77°F (25°C) and higher viscosity at 140°F (60°C)], contained more "polymeric" content (higher LMS content), and were more oxidized (higher C=O and N—O content) than those recovered from batch (pug mill) mixes.
4. Asphalts recovered from recent drum dryer operations are harder than those recovered from drum dryer operations occurring 15 yr ago.

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